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Reduction of crosstalk in mixed CNT bundle interconnects for high frequency 3D ICs and SoCs

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***Abstract* –This paper investigates the multi equivalent single conductor (MESC) model for mixed CNT bundles (MCBs) which contains metallic single and double walled CNTs at the core and semiconducting single walled CNTs at the periphery. This structure shows the least delay due to crosstalk.**

***Index terms* – crosstalk, interconnects, carbon nanotubes, tunneling**

I. INTRODUCTION

Carbon nanotubes (CNTs) are considered as the proper replacement of copper for future on- and off-chip VLSI interconnects. The single-walled CNTs (SWCNTs) and multi-walled CNTs (MWCNTs) were extensively studied as local, intermediate and global VLSI interconnects. SWCNTs are good for local interconnects, while MWCNTs or double wall CNTs (DWCNTs) are good for global interconnects and 'via' applications. Recently, we have studied CNT bundles that contain both SWCNTs and MWCNTs, called mixed CNT bundles [1]. It reveals that MCBs offer less delay in comparison to SWCNT and MWCNT based interconnects. Inter-CNT effects in MCBs were studied and hence optimal placement of various CNTs in the bundle was predicted [2]. Earlier works say that MESC is a more effective approach for lesser percentage of error than multi conductor transmission line (MTL) model [3-6]. In this letter, we show how to reduce the maximum delay due to crosstalk in MCBs by using DWCNTs and semiconducting SWCNTs with the help of MESC approach.

II. PROPOSED STRUCTURE

MWCNTs play a very important role in MCBs since they can carry more signals at high frequencies as compared to SWCNTs. The shells in an MWCNT are closely bound due to the weak π bonds that exist in each CNT shell. So, this makes them more attractive as core conductors rather than peripheral shields. We assume that all shells in an MWCNT are either metallic or semi-metallic in nature. So, at high frequencies, all the shells in an MWCNT conduct current. Thus, it is more appropriate to consider both metallic SWCNTs and DWCNTs at the core and semiconducting SWCNTs at the periphery. Keeping this in mind, we propose a new structure as shown in Fig. 1. where the core has metallic SWCNTs and DWCNTs and the periphery contains semiconducting SWCNTs.

Krupke, R. *et al* (2004) [8] reported a method to separate semiconducting CNTs from metallic CNTs using their electric field induced polarizabilities. So, we emphasize the use of semiconducting SWCNTs as peripheral shielding material to reduce crosstalk among neighboring CNT wires.

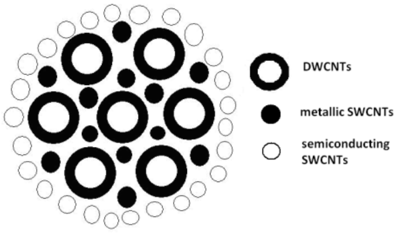


Fig. 1. Schematic of mixed CNT bundle proposed for MESC model.

III. MESC MODEL OF MCBS

Double walled CNTs were grown and characterized for NEMS applications by Hayashi and Endo (2011) [9]. Crosstalk analysis of DWCNT interconnects was done earlier by Pu *et al*, (2009) [10] and they confirmed that DWCNT bundles are better than SWCNT bundles in terms of performance and delay.

Fig. 2 shows the MESC circuit of the MCB that we consider here for analysis. Depending on the number of sub-bands that cross the Fermi level, we can define the number of conducting channels as [6],

$$n_i = \begin{cases} k_1 T r_i + k_2, r_i > r_0/T \\ 2/3, r_i < r_0/T \end{cases} \quad \textbf{(1)}$$

where T is expressed in kelvin, r_i radius of the i^{th} shell in nm, $k_1 = 3.87 \times 10^{-4}\ nm^{-1}K^{-1}$, $k_2 = 0.2$, $r_0 = 1300 nm.K$.

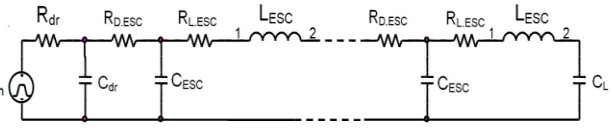


Fig. 2 Equivalent Single Conductor circuit of MCB

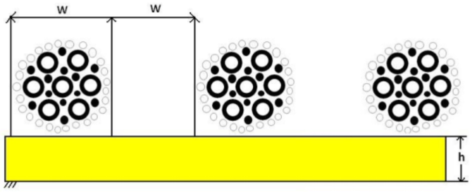


Fig. 3. Three coupled MCB interconnects on a substrate.

Fig. 3 shows the schematic of three coupled MCB interconnects. The per unit length (p.u.l) RLC parameters of an MCB were discussed in detail earlier [2, 3]. The resistance of a CNT is divided into its equivalent lumped part and distributed part. For a DWCNT, we can write the lumped resistance as,

$$R_{L.ESC}(i) = \frac{R_q}{4n_i} \tag{2}$$

where R_q=25.818kΩ. The distributed resistance is,

$$R_{D.ESC}(i) = \frac{R_q}{2(n_i\lambda_i)} \tag{3}$$

The per unit length capacitance equation for a mixed CNT bundle is [2],

$$C_{ESC} = \left[\frac{1}{C_{Q.SW}} + \frac{1}{C_{E.SW}} + \frac{1}{C_{DW}}\right]^{-1} \tag{4}$$

where $C_{Q.SW}$ and $C_{E.SW}$ are quantum and electrostatic capacitance of SWCNTs, respectively and $C_{DW} = C_{E.ESC}+C_{Q.ESC}+C_{C.ESC}$. The value of C_Q per channel is roughly 193aF/µm. The ESC equation for the per unit length inductance is,

$$L_{ESC} = L_{k.ESC} + L_{m.ESC} \tag{5}$$

Recently, Lee, *et al* (2012) [11] reported improved CNT contact treatment after chemical mechanical planarization (CMP) to reduce the contact resistance. They have reported values as low as 85 ohms. Therefore, we can assume that the contacts are nearly ideal and such small values of resistance will not affect the effective mean free path of the wire. Hence, we have not considered the inter-CNT capacitance and the inter-CNT tunneling conductance in our ESC model.

IV. CROSSTALK ANALYSIS AND DELAY CALCULATIONS

One of the main advantages of using semiconducting CNTs at the periphery is to reduce the coupling capacitance effects between adjacent lines. Also, the electrostatic capacitance between the wire and the substrate can be reduced by placing the right amount of semiconducting CNTs at the periphery.

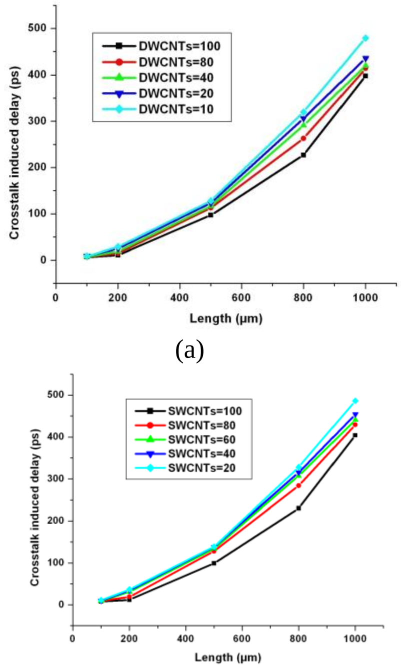
After considering appropriate driver, load resistance and capacitance values [2], a pulsed voltage is applied to the interconnect circuit.

Fig. 4 shows the comparison of length versus crosstalk induced time delay for various counts of SWCNTs and DWCNTs in the MCB. We consider all the parameters according to the ITRS-2007 interconnect report for 22nm and 14nm technology node.

V. RESULTS AND DISCUSSIONS

Crosstalk induced delay for interconnects of 100 to 1000µm is analyzed for a fixed number of SWCNTs and varying the count of DWCNTs in the bundle. The same is done by varying the count of SWCNTs with constant number of DWCNTs. It is observed that as length increases, the delay also increases. The delay has been increased drastically in those bundles that have less number of CNTs. The crosstalk induced delay for the best and the worst cases are shown along with the delay values of other MCBs. TABLE I shows the delay values for the best and worst cases along with the improvement in delay among the two cases.

It is observed that MCBs with more DWCNTs show least delay compared to that of more SWCNTs at the core. The reason is semiconducting CNTs are structurally dissimilar with respect to metallic CNTs, and oppose electron tunneling into the inner tubes as the weak π bond interaction is absent here. Thus they reduce the overall delay of the wire. It is evident that our best case MCBs shows the best performance improvement at 200µm. It means they are suitable as short intermediate interconnects at 14nm technologies.



(a)

(b)

Fig.4 Crosstalk induced delay at different lengths for (a) no. of SWCNTs = 10 and different no. of DWCNTs in the bundle, (b) no. of DWCNTs = 10 and different no. of SWCNTs in the bundle.

TABLE I

IMPROVEMENT IN DELAY FOR THE BEST CASE AND WORST CASE DELAYS IN THE MCB FOR VARIOUS CNT COUNTS

Length (µm)	Crosstalk induced delay (ps)		Improvement in delay for the best case w.r.t the worst case (%)
	SWCNTs=10, DWCNTs=100 (best case)	SWCNTs=10, DWCNTs=10 (worst case)	
100	7	11	36.37
200	11	37	70.28
500	97	139	30.22
800	227	328	30.8
1000	398	486	18.11

The improvement in delay for our best as well as the worst cases, when compared to other MCB structures from [7], is presented in TABLE II. It is observed that, our best case MCBs fare better indicating that they are ideal as local and intermediate interconnects when compared to the structure in [7]. The delay is lesser in our worst case MCBs as compared to the best case in [7] which is due to the presence of DWCNTs at the core of our structure.

TABLE II
IMPROVEMENT OF CROSSTALK INDUCED DELAY FOR VARIOUS CONFIGURATIONS OF MCBs

Length (µm)	Crosstalk induced delay (ps)		Improvement in delay for our best case w.r.t the best case in [7] (%)	Improvement in delay for our worst case w.r.t the best case in [7] (%)	Improvement in delay for our worst case w.r.t the worst case in [7] (%)
	Best case MCB delay in [7]	Worst case MCB delay in [7]			
100	14	29	50	21.43	62.07
200	31	67	64.52	16.22	44.78
500	138	321	29.72	0.72	56.7
800	331	797	31.42	0.91	58.85
1000	504	1225	21.04	3.58	60.33

TABLE III
COMPARISON OF DELAY VALUES BETWEEN MCBS AND MWCNTS

	Crosstalk induced delay (ns)				
Length (µm)	SWCNTs=10, DWCNTs=100 (best case)	SWCNTs=100, DWCNTs=10 (worst case)	MWCNTs (no. of shells=10) [11]	MWCNTs (no. of shells=20) [11]	MWCNTs (no. of shells=30) [11]
100	.007	.011	0.302	0.265	0.252
200	.011	.037	0.390	0.311	0.283
500	.097	.139	0.782	0.468	0.377
800	.227	.328	1.476	0.656	0.493
1000	.398	.486	2.176	0.827	0.572

Comparison of our MCB structures with MWCNTs with various shell counts [12] is shown in TABLE III. It is evident that delay values of MCBs are lesser in one to three orders of magnitude than that of MWCNT interconnects. This can be attributed to the enhanced EMI protection that semiconducting SWCNTs offer to our structure. Also, the improved contact treatment and hence the reduced contact resistance of DWCNTs contributes to the reduction of delay as opposed to MWCNTs which have multiple shell contacts.

VI. CONCLUSIONS

Multi equivalent single conductor (MESC) analysis was carried out for a mixed CNT bundle interconnects that has both DWCNTs and metallic SWCNTs at the core and semiconducting SWCNTs at the periphery. Crosstalk induced time delay was calculated for various counts of CNTs in the bundle and compared with corresponding delay values of MWCNTs from the literature. Then we have compared the percentage improvement of delay among the best and worst cases and also with MWCNTs with various shell counts. It was found that MCBs with the proposed configuration are better candidates for local, intermediate and global interconnect applications than MWCNTs and other MCB structures.

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